Performance Evaluation and Demonstration of Real-Time Vehicle Control Information Exchange Using 5G New Radio Sidelink for Automated Follower Truck Platooning

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SUMMARY  Fifth generation mobile communication system (5G) mobile operators need to explore new use cases and applications together with vertical industries, the industries that are potential users of 5G, in order to fully exploit the new 5G capabilities in terms of its application. Vehicle-to-Everything (V2X) communications for platooning are considered to be one of new 5G use cases whose ultra reliable and low latency communication (URLLC) aspects are required. The authors build a field experimental environment, towards application to truck platooning, with actual large-size trucks and a prototype system, for 5G New Radio (NR) technology based V2X communications. Its most distinctive feature is that the 5G NR-V2X prototype system is equipped with UE-to-UE radio interface (i.e., sidelink) for V2V Direct communication, in addition to the traditional radio interfaces between BS and UE for V2N/V2N2V communications. This paper presents performance evaluation and demonstration of real-time vehicle control information exchange using over the sidelink of 5G NR-V2X prototype system for automated follower truck platooning. This paper evaluates the V2V Direct communication latency and reliability performance of the sidelink, and clarifies 5G NR sidelink achieves lower peak of latency and higher packet reception rate in V2V Direct communication performance than an optical wireless communication system product. Then, it also introduces a 5G URLLC use case demonstration of automated follower truck platooning trial employed with the prototype system in a public expressway environment.

key words: 5G, Sidelink, V2V Direct, Automated Follower Truck Platooning

1. Introduction

Research and development efforts of Fifth Generation Mobile Communication System (5G) are underway for its evolution and beyond [1], [2], although the commercial services of 5G have been already started in major countries around the world from 2020. 5G supports not only enhanced Mobile Broadband (eMBB) but also Ultra Reliable and Low Latency Communication (URLLC) and massive connections for Machine Type Communication (mMTC) [3], [4]. URLLC and mMTC in particular have potential for developing new markets, and it is urgent to establish concrete 5G applications using the capability of URLLC or mMTC. In Japan, the Ministry of Internal Affairs and Communications (MIC) has carried out 5G system trials from 2017. These trials have requested evaluation of 5G wireless system technologies for commercial use, as well as trials of 5G in collaboration with vertical sectors other than 5G mobile operators. Automated driving, including truck platooning [5]–[10] is one of the promising new 5G application areas because 5G offers the ultra-low latency and ultra-high reliability required for the application areas of automated driving. Therefore, the authors have actively participated the MIC’s trials as a member of one of the trial groups, and which focuses a 5G URLLC aspect [11].

It is expected that automated follower truck platooning will contribute to solving several social problems related to truck logistics, such as shortage of truck drivers, their severe work environment, and cost of logistics. Especially, in Japan, the labor force rapidly is shrinking due to a declining birthrate and aging population, as well as the age composition of truck drivers is also skewing upward. This causes shortage of truck drivers and their overworking, which are becoming crucial social issues. These issues increase traffic accidents. The introduction of the automated follower truck platooning is expected to improve the working environment of the truck drivers and to reduce traffic accidents. Therefore, we have been working on use cases of truck platooning utilizing 5G New Radio (NR) technologies to demonstrate the ultra-low-latency transmission capabilities with the over-the-air latency of below 1ms, the network end-to-end (E2E) latency of below 10ms in our trial project [11].

Meanwhile, the 3rd Generation Partnership Project (3GPP) has been recently discussing on requirements of 5G New Radio (NR) enhancements for Vehicle-to-Everything (V2X) communication service which includes, in particular, support of Vehicle-to-Vehicle (V2V) Direct communication over sidelink (SL) radio interface between user equipment nodes (UEs) [12], [13], as well as downlink (DL) and uplink (UL) radio interface between base station (BS) and UE. On the other hand, in 2017 our first 5G field trials [11], V2V Direct communication tests have not been carried out, although we have present field evaluation results on over-the-air transmission performance of Vehicle-to-Network (V2N) communication over the downlink and the uplink of an experimental system, V2V Direct communication tests have not been carried out. This is because the 5G experimental system of the first trials had not implemented sidelink radio interface. In the 2017 trials [11], we have also clarified that V2N and Vehicle-to-Network-to-Vehicle (V2N2V) communications suffer from over-the-air transmission performance degradation at the points far from BS antenna site (i.e., cell boundary) and that it is difficult for V2N and
V2N2V communications to provide stable communication for vehicle-message communications of truck platooning. Then, in order to provide more stable V2V communication for truck platooning, we have developed a new 5G NR-V2X prototype system equipped with UE-to-UE direct communication link interface (i.e., sidelink) for V2V Direct communication before 3GPP defines the detail specifications, in addition to traditional communication radio links between BS and UE (i.e., downlink and uplink) for V2N communication or V2N2V communication [14]. In 2019 our second 5G field trials [14], the authors have built a field trial environment with actual large-size trucks and the prototype system in an automotive test course environment, and the field trial results clarify that 5G V2V Direct communication achieves superior low latency performance compared to 5G V2N2V communication. In 2020 our third 5G filed trials [15], [16], we experimentally evaluated the latency and the reliability performance using pseudo packet in a public expressway environment and these results clarify that 5G V2V Direct communication achieves the peak performance with the over-the-air latency of below 1ms and the reliability of above 99.999% corresponding to a general 5G URLLC requirement [4].

However, in the above our existing previous works [14]–[16], pseudo packets were generated by the UE and the latency and the reliability performance were evaluated by transmitting the pseudo packets between UEs instead of actual vehicle control packets for automated follower truck platooning. This means that the above our previous works [14]–[16] have not yet evaluated the transmission performance on actual vehicle control information exchanged between vehicles’ electrical control units (ECUs) for automated follower truck platooning and that the UEs of 5G NR-V2X prototype system have not connected to the ECUs. In order for us to obtain a government office permission for applying the 5G prototype system to automated follower truck platooning on public expressway in Japan, it has been required that we show end-to-end (E2E) transmission performance including the influence of processing delays inside the ECUs. It is impossible that the E2E communication latency including the delays occurring inside the ECUs is evaluated in the performance evaluation using pseudo packets generated at UEs outside the ECUs. Moreover, it is also impossible that the ECUs receive pseudo packets due to the function limitation. Therefore, in order to evaluate the E2E communication performance, we need to communication tests using real ECUs, in which each ECU receives the actual vehicle control information exchanged among the ECUs. In actual expressway environments, there are places where the platooning vehicles cannot avoid lane changings, such as points where the number of lanes increases or decreases. The lane changings cause misalignment of the optical axis of OWC systems in the platooning use case. This means that it is difficult for V2V communication using only OWC systems to always avoid the transmission performance degradation such as the packet losses of vehicle control messages due to the misalignment of the optical axis. On the other hand, in the case of short-range communications such as V2V Direct, wide beamwidth antennas can be applied for 5G. Therefore, we consider that 5G can overcome the problem in V2V Direct communication for platooning if using wide beamwidth antennas such as omni-directional antennas at the UE sides, since the transmission performance degradation can be ignored due to the misalignment of the antenna beam direction. In order to demonstrate that 5G V2V Direct communication is capable for automated follower truck platooning, it is very important to clarify both the low E2E latency and the high packet reception rate characteristics in the vehicle control information exchange with actual vehicle control packets compared to the OWC system. This is because the low E2E latency and the high reliability are required to the V2V communication link for the automated follower truck platooning. Therefore, this paper evaluates the communication latency and reliability of 5G V2V Direct between ECUs compared to those of OWC system, when each UE of the prototype system connects to ECUs of actual experimental platoon trucks, and it also presents a field trial of automated follower truck platooning on public expressway as a new 5G use case demonstration in order to assess its URLLC capabilities.

The rest of this paper is organized as follows. Section 2 presents the overview of our developed 5G NR-V2X prototype system. Section 3 describes the latency and the reliability performance evaluation of the V2V Direct communication over the sidelink of the prototype system for the real-time vehicle control information exchange. Section 4 describes a use case demonstration of automated follower truck platooning applied with 5G V2V Direct communication. Finally, this paper is concluded in Section 5.

2. Overview of 5G NR-V2X Sidelink Prototype System

This section introduces our developed 5G NR-V2X prototype system with sidelink (SL) [14]. Fig. 1 illustrates the overall configuration of the prototype system with the view of applying 5G to truck platooning. As shown in Fig. 1, the 5G prototype system is roughly divided into an experimental base station (BS) side and an experimental mobile station (MS) side. The BS side is comprised of a core network equipment (CNE), and a base station equipment (BSE) which consist of a base band unit (BBU) and a radio frequency and antenna unit (RAU). The MS side is comprised of three user equipment nodes (3UEs) i.e., UE#1, UE#2, and UE#3. These UEs are placed at three platoon truck vehicles, respectively. Note that we define backward link as a link
from a following vehicle to a preceding vehicle, and that also define forward link as a link from a preceding vehicle to a following vehicle, as shown in Fig. 1.

Fig. 2 illustrates the radio frame structure of the prototype with the radio frame length of 10 ms and the time slot length of 0.25 ms. As shown in Fig. 2, the radio frame is comprised of 40 time slots, the first and the second time slots are special time slots used for synchronization signals of downlink and sidelink, respectively. Table 1 summarizes the major radio specifications of the prototype system. As shown in Fig. 2 and Table 1, the prototype system employs some 5G NR technologies, such as self-contained Time Division Duplex (TDD) frame structure, short transmission-time-interval (TTI), Polar coding, and so on. The channel coding scheme of the prototype system is partially different from that of 3GPP compliant NR. In 3GPP compliant NR, Polar coding is used for control and broadcast channels, and Low Density Parity Check (LDPC) coding is used for data channels. On the other hand, in the prototype system, Polar coding is used for data channels as well as control and broadcast channels.

As shown in Fig. 1 and Table 1, the prototype system is equipped with SL corresponding to UE-to-UE direct communication link for V2V Direct communication, as well as the traditional Uu [1] radio interface of DL and UL for V2N or V2N2V communications. As shown in Fig. 2, the prototype system orthogonally multiplexes DL, UL, and SL OFDM symbols in time domain, in order to avoid interference among DL, UL, and SL. Each time slot is comprised of 14 OFDM symbols. In each time slot, three OFDM symbols are used for DL, UL, and SL, respectively. The rest of OFDM symbols are used for Guard Period (GP) of each link. In the prototype system, the first GP between DL and UL has two OFDM symbols, the second GP between UL and SL has also two OFDM symbols, and the last GP between SL and DL has one OFDM symbol, respectively. Please note that the time slot configuration of the prototype system is different from that of the 3GPP-compliant system, and that the usage of the OFDM symbols within each time slot is unique to the prototype system.

Meanwhile, 3GPP also defines two SL communication modes of “BS In-Coverage mode” (i.e., SL Mode-1) and “BS Out-of-Coverage mode” (i.e., SL Mode-2) [13]. In SL Mode-1, BS schedules the SL radio resources. In SL Mode-2, each UE autonomously selects own radio resources. Even if there are many UEs, SL Mode-1 possibly achieves less inter-user interference (IUI) than SL Mode-2. However, SL Mode-1 is not available at out-of-coverage area of BS, such as inside of tunnels and mountain areas, since the radio resource assignment is controlled by BS side. On the other hand, SL Mode-2 is available in out-of-coverage area as well as in-coverage area, although IUI is possibly occurred by many UEs due to the autonomous radio resource selection [16]. For the detailed descriptions of SL Mode-1 and SL Mode-2, see literatures [19]–[22]. As shown in Table 1, the prototype system supports two sidelink communication modes of SL Mode-1 and SL Mode-2 [13], suitable for BS in-coverage and out-of-coverage areas, respectively [16]. Note that the prototype system does not implement dynamic radio resource allocation and the radio resource assignments to all the three UEs are fixed so as to avoid inter-user interference (IUI) among the UEs [16]. This is because we assume that only three experimental UEs should be considered and it is not required to consider co-channel interference from other UEs or other radio systems. This means that our works in this paper does not assume the influence of the co-channel interference to the wireless transmission performance sidelink. Therefore, our future works include field performance evaluation tests of the sidelink in consideration to the co-channel interference, since the co-channel interference possibly causes the transmission performance degradation.

### 3. Performance Evaluation of Real-Time Vehicle Control Information Exchange for Truck Platooning

#### 3.1 Evaluation Conditions

We carried out field performance evaluation tests of real-time vehicle control information exchange transmitted over the sidelink of 5G NR-V2X prototype system on the road of a public expressway. This section describes the evaluation
conditions. Fig. 3 shows the evaluation test environment and the evaluation course with the lengths of about 15 km from point #a to point #c along Shin-Tomei Expressway at a rural high land area in Shizuoka Prefecture, Japan.

Fig. 4 illustrates the test configuration and Fig. 5 shows the appearance of the major equipment components for the evaluation tests. As shown in Fig. 4 and Fig. 5 (a), three platoon trucks #1-#3 were used. Each ECU of each platoon truck, shown in Fig. 5 (b), was put in the driver’s cabin, and each UE of the 5G NR-V2X prototype system, shown in Fig. 5 (c) was installed in the cargo box of each platoon truck. As shown in Fig. 5 and Fig. 5 (d)-(f), three 5G UEs were placed in the cargo container of the trucks, respectively. The UE antennas were mounted on the rooftop of the driver’s cabin. From Fig. 4, each UE was connected to ECU of the platoon truck by wired Ethernet in order to transmit and receive the vehicle control information of each ECU among the trucks. As shown in Fig. 4, all the ECUs are time-synchronized using Global Navigation Satellite System (GNSS), in order to measure the communication latency including the influence of processing delays occurring inside the ECUs. Each ECU sends vehicle control information packets after the transmitted timing information is attached to their packet header. Other ECUs measure the communication latency by calculating the difference between the transmitted timing information attached to the packet header and the received timing information.

In the tests, the performance results of 5G NR sidelink were compared to those of an OWC system product using near-infrared LED communication technology developed by Fraunhofer Heinrich Hertz Institute [23], [24], since the OWC system product have been already embedded into the existing experimental vehicles for automated follower truck platooning trials, shown in Fig. 5 (a), as one of V2V communication systems. Therefore, it is required that the 5G NR sidelink achieves lower E2E latency and higher packet reception rate in V2V Direct communication than the OWC system in order to apply 5G NR sidelink to the automated follower truck platooning trials. As shown in Fig. 4 and Fig. 5 (g)-(j), the transmitter and receiver (TRx) units of the OWC system were installed at the front grille or the rear bumper of the experimental trucks and they were also connected to the

![Image](image_url)

**Fig. 3** Performance evaluation test environment and course.

![Image](image_url)

**Fig. 4** Performance evaluation test configuration.

![Image](image_url)

**Fig. 5** Appearance of major equipment components for field performance evaluation tests of vehicle control information exchange.

### Table 2 Major radio specifications of OWC system product for comparison.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Access Scheme</td>
<td>IEEE 802.15.13 (Draft) [23]</td>
</tr>
<tr>
<td>Center Carrier Wavelength</td>
<td>850 nm</td>
</tr>
<tr>
<td>Maximum Optical Clock Rate</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Duplex</td>
<td>Full Duplex</td>
</tr>
<tr>
<td>Waveform Type</td>
<td>Direct Current-based Optical OFDM [24]</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>195.3125 MHz</td>
</tr>
<tr>
<td>Channel Coding</td>
<td>Low Density Parity Check (LDPC) Coding</td>
</tr>
<tr>
<td>Retransmission scheme</td>
<td>Hybrid Automatic Repeat reQuest (HARQ) with Chase Combining</td>
</tr>
<tr>
<td>Typical End-to-End Latency</td>
<td>below 2 ms [17],[18]</td>
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</table>
Table 3 Major evaluation parameters.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>Common parameters for 5G NR sideline</td>
<td>Target vehicle speed</td>
</tr>
<tr>
<td></td>
<td>Target inter-vehicle distance</td>
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<tr>
<td></td>
<td>Transmission interval of</td>
</tr>
<tr>
<td></td>
<td>vehicle control message</td>
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<tr>
<td></td>
<td>packets from ECUs</td>
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<tr>
<td></td>
<td>Latency measurement interval</td>
</tr>
<tr>
<td></td>
<td>at ECUs</td>
</tr>
<tr>
<td>5G UE antenna type</td>
<td>+45° polarized omni-directional antennas</td>
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<tr>
<td>5G UE antenna height from ground</td>
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<tr>
<td>5G UE antenna distance</td>
<td>UE#1-UE#2, UE#2-UE#3: about 22 m</td>
</tr>
<tr>
<td></td>
<td>UE#1-UE#3: about 44 m</td>
</tr>
<tr>
<td></td>
<td>Vehicle length of trucks: 12 m</td>
</tr>
<tr>
<td></td>
<td>Target inter-vehicle distance: 10 m</td>
</tr>
<tr>
<td>5G sidelink communication mode</td>
<td>SL Mode-2 (BS Out-of-Coverage Mode)</td>
</tr>
</tbody>
</table>

Fig. 6 Examples of communication latency observed inside ECUs

ECUs by wired Ethernet, respectively. Note that two TRx units of the OWC system were installed at both the front grille and the rear bumper at the experimental truck#2, in order to relay the vehicle control message between ECUs of Truck#1 and Truck#3 since the optical wireless link of general OWC systems require the visibility between two TRx units. Table 2 summarizes the major radio specifications of OWC system. As shown in Table 2, the specifications are based on a draft of IEEE P802.15.13 [23] with the waveform type of Direct Current-biased Optical Orthogonal Frequency Division Multiplexing [24].

Table 3 summarizes the major evaluation parameters. As shown in Table 3, in the evaluation tests, each ECU periodically transmitted actual vehicle control information with the packet payload size of 105 bytes/packet to the other platoon trucks over wireless V2V communication links (i.e., 5G NR sidelink or optical wireless link) every 20 ms and that it received vehicle control information transmitted from the other platoon trucks over the links. Note that the packet payload size and the packet transmission interval were common for 5G NR sidelink and OWC system. Each ECU periodically measured the communication latency measurement results every 10 ms. In the tests for 5G NR sidelink, omni-direction antennas are applied at each UE, in order to avoid the wireless transmission performance degradation due to the misalignment of the antenna beam direction among the UEs. Note that it is impossible that the measurement interval was shorter than 10 ms due to the processing speed limitation of the ECUs. In this evaluation, SL Mode-2 is only applied as a sidelink communication mode, respectively. This is because the trial course for automated follower truck platooning demonstration described in Section 4 includes inside of tunnels and it is difficult that we deploy the experimental BS and that the inside of tunnels is served by the experimental BS.

This test was carried out under the condition of mixing with other general vehicles and there were road noise barrier walls on the road side of a part of the evaluation course. Moreover, in this test, there were lane changes three times at the points with the distance of about 0.5 km, 3.2 km and 14.9 km away from the starting point #a. Note that the lane changes possibly degrade the transmission performance of OWC system since they cause misalignment of the optical axis of OWC system. The inter-vehicle distance values of Truck#1-Truck#2 and Truck#2-Truck#3 varied while the testing. The median values are 8.7 m and 8.9 m, the standard deviations are 0.4 m and 0.5 m, the minimum values are 7.7 m and 7.8 m, the maximum values are 10.1 m and 10.4 m, respectively.

3.2 Evaluation Results

Fig. 6 shows examples of the V2V communication latency observed inside the ECUs versus the traveling distance of the leading vehicle from the start point #a. Fig. 6 (a) plots the characteristics in the case of 5G NR sidelink and Fig. 6 (b) plots those in the case of OWC system, respectively. Fig. 7 shows the complementary cumulative distribution function (CCDF) characteristics of the V2V communication latency observed inside the ECUs. Fig. 7 (a) plots the characteristics of the backward links from the preceding trucks to the following trucks, and Fig. 7 (b) plots those of the forward links from the following vehicles to the preceding vehicles, respectively. In these figures, the solid lines represent the characteristics of 5G NR sidelink, and the dashed lines represent those of OWC system. Fig. 7 (a) and Fig. 7 (b) find that the communication latencies are about 21 ms and 31 ms at the CCDF values of $10^{-2}$ in the case of 5G NR sidelink and OWC system, respectively. When the communication latency values at the CCDF values of $10^{-2}$ are evaluated, the results of Fig. 7 (a) and Fig. 7 (b) also find that 5G NR sidelink has the communication latency characteristics about 10 ms lower than that of OWC system.

Table 4 summarizes the packet reception rate results of the V2V communication observed inside the ECUs. From Table 4, we find that 5G NR sidelink achieves the high reliability performance of 99.998 % or above. On the other hand, from Table 4, we also find that the packet reception rates
ment of optical axis of OWC systems, the authors considers the starting point \( a \). Since lane changings cause misalignments near \( c \) (with the distance of about 14.9 km away from the inside of tunnels). The packet losses of OWC system occurred continuously at the road noise barrier walls. On the other hand, the lane changing causes of the packet losses of OWC systems.

The above latency and reliability test results demonstrate that the largest latency of 5G NR sidelink is less than that of OWC system, and that the packet reception rate of 5G NR sidelink is larger than that of OWC system. These test results confirms that 5G NR sidelink enables the real-time vehicle control information exchange for automated follower truck platooning.

4. 5G Use Case Demonstration of Automated Follower Truck Platooning Trial on Public Expressway

4.1 Trial Conditions

We carried out a 5G use case demonstration of automated follower truck platooning trial in a public expressway environment. In this trial, the platoon trucks applied both CACC [8] and ASC of the trailing vehicles [10] by connecting our developed 5G NR-V2X prototype system to the ECUs of actual experimental platoon trucks, in order to promote the ultra-reliability and low-latency capability of 5G. In this trial, the automated driving was applied at the trailing vehicles based on the inter-vehicle control information exchanged over the sidelink of the prototype system. Note that the sidelink communication mode of only SL Mode-2 is also applied in this trial and SL Mode-1 is not applied. This is because the demonstration environments include inside of tunnels and it is difficult that we deploy the experimental BS and that the inside of tunnels is served by the experimental BS. Each trailing vehicle was equipped with two Light Detection And Ranging (LiDAR) sensors. In this trial, at each trailing vehicle, one of the LiDAR sensors was used to follow the preceding vehicle automatically, and the other was for redundancy.

Fig. 8 shows the demonstration environment and the trial course on the public expressway. The trial course with the lengths of about 30 km is located at Shin-Tomei Expressway in Shizuoka Prefecture, Japan. As shown in Fig. 8, the trial course from \#A to \#G includes two tunnels, the points from \#B to \#C are inside one of the tunnels, and the points from \#D to \#E are inside the other tunnel. The platoon trucks travelled along the trial course shown in Fig. 8 so as to maintain a target inter-vehicle distance.

![CCDF of V2V communication latency observed inside ECUs.](image)

![Demonstration trial course (Course lengths : about 30 km)](image)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>From</td>
<td>to</td>
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<tr>
<td>Truck#1</td>
<td>Truck#2</td>
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<tr>
<td>Truck#1</td>
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<td>Truck#2</td>
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Fig. 7 CCDF of V2V communication latency observed inside ECUs.
Fig. 9 illustrates the system configuration of the vehicle-control message transmission for CACC and ASC. As shown in Fig. 9, the platoon trucks are composed of a leading vehicle piloted by a driver and two trailing vehicles with automated driving control. In this trial, the vehicle-control messages, including speed and position messages, are exchanged among the ECUs of all the platoon trucks, each other. The ECUs provide the functions of CACC and ASC in the platooning. The CACC function automatically adjusts the accelerator and the break of each trailing vehicle based on the vehicle control information so as to maintain the target inter-vehicle distance. The ASC function adjusts the steering angle of each trailing vehicle based on the vehicle control information so as to follow the trajectory of the preceding vehicle automatically.

In this trial, the ECUs adjusted the target inter-vehicle distance according to the vehicle speed of the leading truck. Fig. 10 plots the relation between the target inter-vehicle distance and the vehicle speed in CACC. As shown in Fig. 10, the target inter-vehicle distance is set to 5m at the vehicle speed of below 20 km/h and set to 9 m at the vehicle speed of over 60 km/h. The target speed of trucks was set to 80 km/h, which is an upper limit of truck speed on the expressway. The driver at the leading vehicle controlled the vehicle speed so as to maintain the target speed as much as possible. Note that the vehicle speed was not always maintained at the target speed since the driver should appropriately adjust the vehicle speed in order to avoid traffic accidents. Note that the payload size of the vehicle control information packets was 105 bytes/packet and that the transmission interval was 20 ms, which are the same as the evaluation condition described in Subsection 3.1.

4.2 Demonstration Trial Results

Fig. 11 shows examples of the truck platooning trial scenes. Fig. 11 (a) and (b) confirm that automated driving was applied at the trailing truck side since the accelerator, the brake, and the steering are automatically controlled in this trial. Fig. 11 (c) to (h) find that this trial was carried out under a practical condition of mixing with other various general vehicles. Fig. 11 (c) to (g) confirm that the platoon trucks maintained with a tight inter-vehicle distance on the course, although the platooning trucks travelled through the various conditions such as tunnel inside, tunnel outside, and curved lane. Moreover, Fig. 11 (h) also confirm that the platoon trucks maintained with the tight inter-vehicle distance while their automatic lane changing.
the inter-vehicle distance. Fig. 12 (a) confirms that the trailing vehicles (i.e., Truck#2 and Truck#3) were maintaining almost the same vehicle speed as the leading vehicle, and Fig. 12 (b) finds that the speed differences are always within about ±5 km/h. Fig. 12 (c) also confirms that the trailing vehicles were maintaining the target inter-vehicle distance. The above trial results demonstrated that 5G is feasible to the capability of automated follower truck platooning, since the sidelink of our 5G NR-V2X prototype system achieved automated driving without human driver assistance at the trailing vehicle sides on the course with the lengths of 30 km.

5. Conclusions

This paper presented performance evaluation and demonstration of real-time vehicle communication exchange V2V Direct communications over the sidelink of our developed 5G NR-V2X prototype towards application to automated follower truck platooning. We first introduced the prototype system and evaluated the V2V Direct communication latency and reliability performance of 5G NR sidelink compared to those of an OWC system, when each UE of the prototype system connects to ECUs of actual experimental platoon trucks. The evaluation results confirmed that 5G NR sidelink achieves lower peak of E2E latency and higher packet reception rate than the OWC system. Then, we presented a 5G use case trial of automated follower truck platooning using 5G NR sidelink in a public expressway environment on the conditions of mixing with other general vehicles. The trial results demonstrated that the ultra-reliability and the low-latency capabilities of 5G is feasible for automated follower truck platooning.

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